Int J Life Cycle Assess (2014) 19:931–940
DOI 10.1007/s11367-013-0697-7

PACKAGING SYSTEMS INCLUDING RECYCLING

Reusable vs. disposable cups revisited: guidance in life cycle comparisons addressing scenario, model, and parameter uncertainties for the US consumer

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Received: 8 May 2013 / Accepted: 31 December 2013 / Published online: 25 February 2014

Abstract
Purpose Despite interest in an environmentally conscious decision between disposable and reusable cups, a comprehensive and current study for US consumers is not yet available. Guidance in favor of single-use cups rely on outdated or non-ISO-compliant results with limited uncertainty information. Such claims are insufficiently generalizable. This article delivers an updated comparative life cycle impact assessment of reusable ceramic cups and single-use expanded polystyrene cups.
Methods The ReCiPe midpoint model was selected. Scenario uncertainties are addressed by evaluating compliant standard dishwashing appliance models from 2004 to 2013 used in 26 US subregional utility grids. A utility snapshot from 2009 is applied with extension to recent shifts in generation from increased penetration of natural gas and renewable energy. Parameter uncertainty is quantified through statistical methods.
Results Where there is statistical difference, results almost entirely favor reusable cups in the USA. For climate change, 16 % of users have higher impact for ceramic cups washed in 2013 by minimally compliant dishwashers. Higher climate change impacts for 32 % of reusable cup users is indicated with 2004 average dishwashers, though using a cup twice between washes shifts the impact in favor of the reusable cup.
Conclusions Disposable cup scenarios do not account for film sleeves, lids, printing, and less conservative shipping weights and distances and therefore reflect a best case scenario. Impact for reusable cups is expected to decrease further as the electricity mix becomes less CO_2-intensive with replacement of coal-fired generators by natural gas, wind, and solar and as less efficient dishwashers are replaced with new units compliant to current laws.

Keywords Sustainability · Uncertainty · Consumer choice · Midpoint impact assessment

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1 Introduction

In 2010, the USA accounted for 37 % of food service disposables globally and is projected to remain the largest market for these consumable goods by a wide margin (Freedonia Group Inc. 2011). Over 500 billion disposable cups are sent to landfills every year (Forsyth 2012). Despite the strong interest in assessing the life cycle footprint of reusable and disposable cups, previous studies have been too narrow in scope for making generalizable claims (Hocking 1994; Ligthart and Ansems 2007). One of the largest shortcomings of the most cited works by Hocking in 1994 and the Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO) in 2007 is the assumption of cup size, which were evaluated at 8 oz or less when the actual average portion size in the USA is around 16 oz (Hocking 1994; Ligthart and Ansems 2007; Nielsen and Popkin 2003). Furthermore, these previous works lack resolution in the feedstock for power generation by assuming a national average and are outdated regarding recent power generation trends. Hocking's work addressed only cumulative energy demand. TNO's publication used CML

2002 and a shadow price approach. Aside from high contribution of ecotoxicity to conclusions in the TNO study and guidance in cautious use of ecotoxicity for policy and decision making (Aboussouan et al. 2004), the conclusions cited by the TNO study further suffer from parameter uncertainty that is not addressed in the report's sensitivity analyses. Nonetheless, these studies have been cited extensively as guidance for consumer purchasing and business operations. A more thorough literature review is available in the Supporting Information.

Analysis in this updated study covers both polyethylene-coated paper (PE-paper) cups and expanded polystyrene foam (EPS) cups for single-use systems with glass, ceramic, and varying plastic blends for the reusable system. Since past research has produced inventories and analyses for EPS versus PE-paper (Franklin Associates Ltd. 2006), iterations of this study lead to a focus on EPS and ceramic cups in parsing results.

Ceramic cups were chosen both for consistency with previous studies and because they tend to have higher impacts than similar reusable plastic cups designed for equivalent life span. Of the reusable cups considered, none are specifically advocated as the most preferred in the scope of this study. Nonetheless, clarity is required in differentiating reusable cups that are used-as-designed for hundreds or thousands of uses and those that fail to maintain emotional durability as defined by Chapman (Chapman 2009) such that they are not utilized fully for a designed life span through loss, breakage, or disfavor. Such matters, though a critical part of research in sustainable consumption, are outside of the scope of this study, which takes the view that 500 uses of a reusable cup conservatively describes true usage. To assume less would bring in social and moral issues in consumption, which cannot be captured by traditional LCA, but are a necessary field of research as part of a toolbox for sustainability. Regarding an adequate and appropriate steady-state approximation, iterations of the analysis found this figure to be well beyond the point at which the use phase dominates the impact entirely for ceramic, glass, and durable plastic cups. Still, results regarding break-even uses for climate change are provided in Supporting Information.

This article contributes to the literature by analyzing an essential consumer item: a drinking cup, where the average US consumer may be presented with the choice between cup types multiple times per day. This study frames the choice realistically according to realized trends in consumer appliance ownership and average portion size. Washing energy is evaluated according to subregional electrical utility mixes instead of a national average. With scenario and model uncertainty addressed in framing the problem, parameter uncertainty is addressed in interpretation of results. The approach taken overcomes shortcomings of previously published findings.

Key findings of the study are the superiority of reusable cups in climate change impact in most regions of the USA with only approximately 32 % of the residential population having a higher climate change impact for the oldest appliance technology assessed. This figure drops to about 16 % for US consumers using a minimally compliant 2013 dishwasher model. This study also finds even for regions with highest climate change impact, reusable cups have comparable or lower impacts in nearly every other indicator of the ReCiPe method. Contrary to prior reports, rinsing a cup and using only twice between washes is sufficient for improving climate change impacts for consumers with dated dishwashers in regions of higher impact. These results indicate a strong life cycle environmental benefit of using reusable cups.

This article begins by laying out assumptions of the model and scenarios evaluated. Then, a comparison to energy analyses of previous studies is provided. From here, a case is made for conducting a midpoint impact assessment according to regional utility mixes rather than national averages using the ReCiPe method. Results of the midpoint assessment are presented using statistical methods for comparing the means of two independent lognormal distributions to determine statistical significance in comparison of results. This is followed by a discussion of results and implications of changing electrical utility mixes and differentiation between residential and industrial purchasing behaviors. The Supporting Information includes a more detailed literature review and background; a comparison to the 2007 TNO study; more information on modeling assumptions, tools, statistical methods, and grid details; additional uncertainty and midpoint graphs; and an extension of results to a regional mix undergoing changes due to increased natural gas and renewable energy penetration in 2012.

1.1 Assumptions and problem design

Many methods and inventory practices have been developed and aided through standardization since the mid-1990s. This study applies process modeling using SimaPro 7.2.4 with Ecoinvent v2 database and a selection of impact methods available in the software. In the analysis, cumulative energy demand (CED), CML 2, TRACI2, and ReCiPe midpoint methods were applied to gain insight on past studies and conflicting results. The ReCiPe midpoint method has been selected for reporting final conclusions based on its more recent development, which has addressed some of the issues in ecotoxicology assessment raised in the CML model. More information on various life cycle impact assessment (LCIA) methods and software can be found in the literature and in the Supporting Information (EarthShift 2011; Ecoinvent Centre 2007; Althaus et al. 2010; Joint Research Commission (JRC) 2010).

The life cycle diagram in Fig. 1 shows activities that form the analytical space, showing only the EPS and reusable models. Ecological flows (emissions, effluents, raw material acquisition, etc.) are implicit to the diagram, from which the inventory is constructed. The following sections discuss the features of the process network.

1.1.1 Cup manufacture and end-of-life

The cup size is 16 oz (473 mL), keeping with current trends and analyses (Franklin Associates Ltd. 2006; Franklin Associates 2011; Nielsen and Popkin 2003). More discussion on cup size is in the Supporting Information. The mass of the disposable cups from the Franklin study in 2006 is used here, which is 4.4 to 5.0 g/cup for EPS (Franklin Associates Ltd. 2006). For the reusable cups, impact has low sensitivity to cup mass within its useful life; a range was applied capturing low- to high-weight retail samples. For ceramic cups, this range was 292 to 700 g/cup.

For both paper and plastic single-use serviceware, recycling is negligible in the US municipal solid waste system (US Environmental Protection Agency (EPA) 2009). In both cases, the US average for solid waste incineration, 11.7 %, is assumed (US Environmental Protection Agency (EPA) 2011). Incineration for energy recovery is considered avoided production. The remaining is assumed to be landfilled. Sensitivity analysis provides sufficient insight for variations in waste handling across regions. There are 86 waste incineration facilities in 24 states by 2010 figures, where the incineration rate would be higher than the cited average (Michaels 2010). Highest throughput facilities are distributed primarily in the northeast, Florida in the south, and Pennsylvania in the midwest. Remaining regions have little to no substantial municipal waste-to-energy activities, so the reality in these areas would approach 100 % landfill for cups disposed in trash receptacles.

Ceramic is not considered recyclable, while less than 15 % of glass containers are recycled annually (US Environmental Protection Agency (EPA) 2009). Both are designated as 100 % landfill.

Corrugated cardboard has a 76.6 % waste stream recovery rate, which is modeled in the disposable cup system (US Environmental Protection Agency (EPA) 2011). It is assumed as a first approximation that 76.6 % of the cardboard packaging is diverted from landfill or incineration with 50 % of diverted materials resulting in avoided production or reuse.

A conservative value was placed evenly on the disposable cups for transportation and packaging. The average distance for delivery of materials and products by diesel truck was set at 200 miles. Packaging for transportation of the raw materials was neglected. Only corrugated cardboard for distribution of the final product at 1,000 units per box. Packaging film sleeves, cup lids, and individual cup sleeves were not included in the inventory. The corrugated cardboard is assumed to add 10 and 20 % to the final shipped product mass for paper and polystyrene cups, respectively. These figures were estimated based on an evaluation of average cup mass and shipping weights and rounded downward. The sum total of these assumptions leads to results that represent a lower limit of impact for the single-use system.

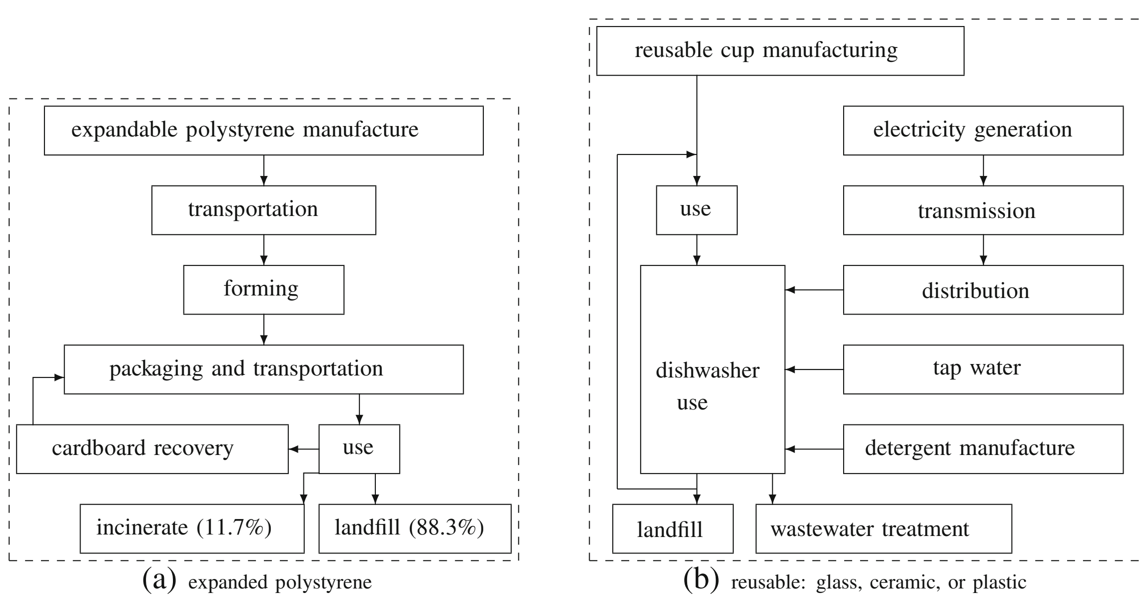


Fig. 1 Technical system life cycle diagram each type of cup

1.1.2 Use phase

Fifty to seventy-five percent of American homes are equipped with a dishwashing appliance (Hoak et al. 2008; Emmel et al. 2003; California Energy Commission (CEC) 2010; Boustani et al. 2010). Thus, from the US consumer perspective, it is assumed, on average, that significant domestic population have access to a dishwasher with relative ease and frequency. Results of this study are transferable to the workplace in the event that a standard-sized dishwasher is provided for employee use within the range of assumptions.

Energy, Water, and Detergent The E-SCOPE study conducted in the UK to inform appliance take-back policies in the mid to late 1990s found that the average age of discarded dishwashers was 9 years (Cooper and Mayers 2000; Cooper 2005). While a Department of Energy analysis yielded a mean age of 15 years based on a Weibull distribution for likelihood of failure (US Department of Energy Office of Energy Efficiency and Renewable Energy (OEERE) 2012; U.S. Department of Energy (DOE) 2012), this study will assume values based on the direct observations of consumer behavior from E-SCOPE. Table 1 lays out values for energy and water use of dishwashers dating back to average purchases in 2004. For current models, energy and water use are cited from Federal Register and Energy Star requirements for compliance and certification (U.S. Government Printing Office (USGPO) 2012; U.S. Environmental Protection Agency (EPA) 2013a; 2013b). Energy use is reported in kilowatt hour per year, including energy use per cycle plus standby power, assuming 215 cycles/year. The energy factors (EF, cycle per kilowatt hour) in Table 1 are derived accordingly.

For earlier years, energy factors represent average consumer purchases, as determined in a report tracking appliance market shares in California prior to incentivization measures (Pulliam 2009). Average EF for dishwashers increased from 0.52 in 1999 to 0.66 in 2007. With the passage of the "Energy Independence and Security Act" of 2007, water efficiency became explicitly part of DOE dishwasher efficiency standards. Energy use in dishwashers is most highly correlated to water use for heating (Hoak et al. 2008). Therefore, for the average purchased dishwasters in 2004 and 2007, water consumption is assumed from the corresponding EF from guidelines. Units having EF of 0.6 and 0.66 correspond to maximum water use of 6.5 and 5.8 gal/cycle, respectively, according to Department of Energy requirements for compliance and energy star ratings (U.S. Government Printing Office (USGPO) 2012; U.S. Environmental Protection Agency (EPA) 2008).

Detergent mass follows from a review of dishwasher operation manuals and consumer tips on labels of powder detergents. A review of material safety and data sheets for detergents and self-reported product ingredient listings showed sodium carbonate (Na_2CO_3) is common and appreciable in concentration. In production of laundry detergents, raw material supply was dominant over total product manufacture, including packaging (Saouter and van Hoff 2002). In order to keep the scope manageable, production of 100 % Na_2CO_3 is assumed as a proxy. Sodium sulfate, sodium chloride, and layered sodium silicate were also included in analysis iterations, but the impact of different formulations was found negligible compared to influences from energy use of the washing unit.

User behavior To fairly allocate the fraction of impact in washing attributed to a single cup, assumptions must be made regarding capacity loading. Dishwashers are designed with a larger volume designated to the bottom rack leaving the top rack to occupy about 40 % of the wash volume. This allows the bottom rack to be reserved for large, unusually shaped items as dinner plates, pots, and pans while the top rack is designed primarily for cups and other small items. Reasoning that 25–30 cups can fit in the upper rack, a conservative assumption is made such that a single cup is allocated a fraction of $\frac{1}{60}$ of the dishwasher capacity, assuming a fully loaded unit. A consumer study found that 93 % of study participants report running their dishwashing appliance only when full (Emmel et al. 2003). Drying cycles are assumed corresponding to compliance testing procedures.

Table 1 Dishwasher energy and water use 2004–2013

Year	Rating	Energy factor cycle/kWh	Water use L/cycle (US gal/cycle)
2004	Average purchase (AP)	0.59	24.6 (6.5)
2007	Average purchase (AP)	0.66	22.0 (5.8)
2013	Minimally compliant (MC)	0.70	18.9 (5.0)
2013	Energy star (ES)	0.73	16.1 (4.25)
2013	Best available technology (BAT)	1.19	8.3 (2.2)

2 Methods

Beginning with an energy analysis, methods of approach were in keeping with trends dating back to the work of Hocking (Hocking 1994). Then, midpoint analysis with attention to uncertainty are presented for a set of reasonably generalizable conclusions for the US consumer. A case is made for disaggregation according to regional utilities, for evaluating this comparison with more recently developed LCIA methods, and for greater attention to be placed on uncertainty for fair reporting. The functional unit for analysis and reporting is impact per use of each cup. The basis of the assumption is one wash or disposal for each use, respectively. Some details have been described underlying the assumptions in this respect, e.g., model energy factor, uses per cup life, and cup mass. More details are in the Supporting Information.

2.1 Energy analysis

The values for energy demand reported by Hocking (1994), Denison (1998), and Franklin Associates Ltd. (2006) are superimposed to this study's energy analysis results in Fig. 2. An extrapolation to Hocking's figures is made for 16-oz cups. In this graph, line spread captures mean values for scenario ranges described above. For disposable cups, variability in cup mass is reflected. For reusable cups, variability in energy and operational efficiencies are captured. Variations include range of cup mass, energy factors, water and detergent use, and capacity loading. Figure 2 takes the approach used by the references cited, combining various energy fuel sources for a cumulative figure, though it is recommended in current practice to report the fuel sources individually. These details are in the Supporting Information.

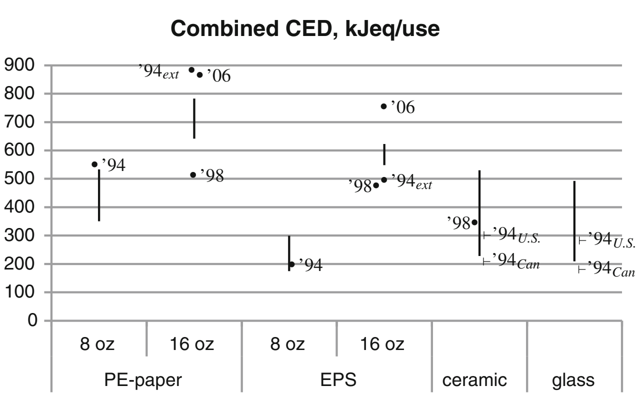


Fig. 2 Comparison of combined cumulative energy demand, notated by year of publication (Hocking 1994; Denison 1998; Franklin Associates Ltd. 2006). *ext*, extrapolation to 16 oz; *Can/U.S*, Canadian and US average electricity generation scenarios

There is agreement in this study's results and previous studies where assumptions have been aligned. While dishwasher use dominates the impacts of reusable cups over the useful life, impact is not similarly affected by size as larger cups occupy about the same amount of space in the unit.

The Franklin Associates study is assumed the most comprehensive and relevant study on disposable serviceware (Franklin Associates Ltd. 2006). Where our figures come in somewhat lower, they are in good agreement and particularly conservative with respect to the Franklin study. Packaging assumptions in this study are more conservative than those in the Franklin study, which would have a larger impact on the polystyrene cups than the paper cups. The Franklin study assumed packaging of 500 units per box, adding corrugated cardboard in the amount 68 and 17 % of the cups' mass for EPS and PE-paper cups, respectively. The figure reported from the Franklin study in Fig. 2 includes packaging and waste-to-energy credits applied in the study for fair alignment of boundaries.

The largest influence on cumulative energy demand across the reusable cups is dishwasher power requirements, which correlates to utility grid assumption, percent of washer capacity loading, and energy efficiency of the unit. Previous studies assume an average national electricity mix and are neither current nor geographically relevant across the USA. Figure 3 expands the utility grid assumption into 26 US regions, in approximate descending order of population, as reported in the EPA's Emissions and Generation Resource Integrated Database (eGRID) (U.S. Environmental Protection Agency (EPA) 2012). The population ordering in this case is to avoid arbitrary data visualization. It is acknowledged that there is a significant cross-regional transmission. This is addressed further in context of uncertainty in the midpoint results and in the discussion section. Subregion names and a breakdown of utility grid mixes for each region is provided in the Supporting Information.

2.2 Midpoint assessment and uncertainty analysis

While comparison with previous studies, including the TNO study (discussed further in the Supporting Information) gives us some information, especially regarding impact correlations to size in disposable cups, the level of resolution is not high enough to accurately demonstrate sensitivity on energy use and other factors for this study. First, model and scenario uncertainties were addressed by disaggregation across subregional utilities, modeled with 2009 data, and accounting for representative dishwasher models spanning older models still in operation to 2013 purchases.

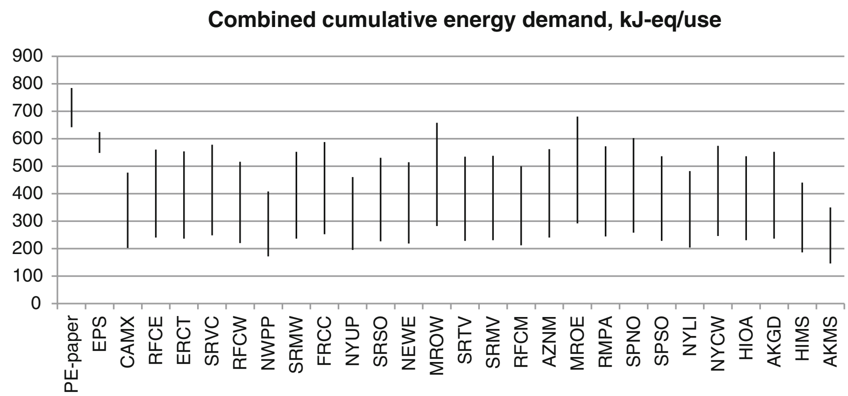


Fig. 3 Combined cumulative energy demand per use of 16-oz cup across regions of US electricity grid

An inventory analysis revealed positive skewness with characteristic mean > median > mode. Nearly all distributions in Ecoinvent v2 unit processes are designated lognormal. Much of the Ecoinvent v2 data has uncertainty information associated with inventory items, which is determined through combinations of measurements, estimates, and a pedigree matrix approach described in literature (Weidema 1998; Ecoinvent 2007). Over 70 % of the inventory for this study contained uncertainty information through these semi-quantitative methods. For comparison in any impact category, an investigation of the measures of central tendency is warranted.

2.2.1 Measures of central tendency

Use of SimaPro's "analyze" and "compare" functions generates mean value output. This is what is generally reported in LCA literature where this software is used for processing inventories. For example, Fig. 4 shows two sets of results for climate change (CC). Figure 4a shows mean output across the range of scenarios, similar to the range shown in Fig. 3, demonstrating utility mix effects. For the single-use cups, variation corresponds to cup mass. For the reusable cups, across the subregions, the range includes user and appliance efficiencies. Figure 4b gives box plots resulting from parameter uncertainty for one scenario, or one combination of sensitivities relating to mass, energy use, etc. The mean value in the box plot, designated by a sideways hash mark, corresponds to the output in Fig. 4a designated with the darkened circle. For other points along the range in Fig. 4a, parameter uncertainty graphs would show a shift in the mean and a corresponding shift in confidence intervals.

Inventory components contributing most to CC in this study have smaller standard deviations designated in the inventory than those having highest contributions to other impacts such as ionizing radiation, human toxicity, and ecotoxicity. Figure 4 is an example where the mean is a reasonable measure of central tendency for comparison of the EPS and reusable cups, and there is greater variation in scenario uncertainty than parameter. On the other hand, where the largest contributors to ionizing radiation (IR) in the inventory have higher uncertainty designation, the spread is much greater, as shown in Fig. 5, such that the comparison of mean values may not accurately reflect differences in impact. Figure 5 is an example where parameter uncertainty has greater influence than scenario. Higher uncertainty may be attributed to a number of factors, including more complex geochemical influences on substances in the ground and water compartments; inventory data quality regarding time, location, and technology; or variation in reporting requirements across industries and regions.

It is known that mean and standard deviation are highly sensitive to extreme points, and it is often recommended by statisticians to use the population median rather than the mean as a measure of central tendency when dealing with a skewed distribution (Singh et al. 1997). For both Figs. 4b and 5b, the whiskers reflect the median plus 1.5 times the interquartile ratio.

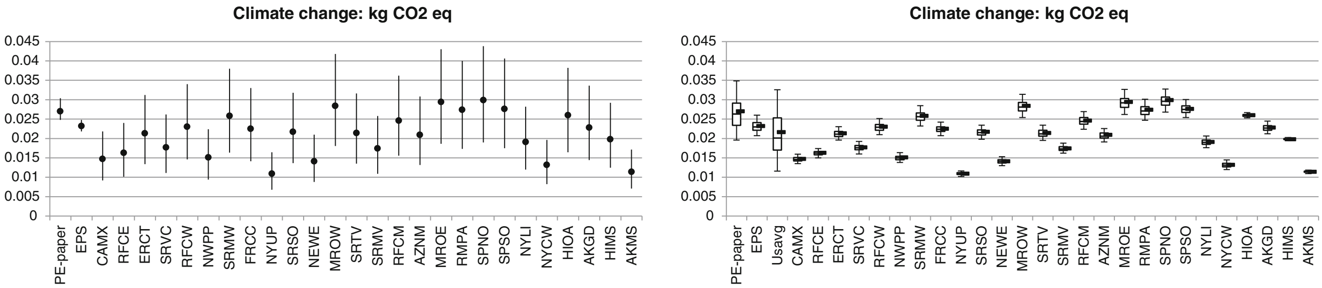
Given the output from SimaPro and basic knowledge on the distributions for each indicator in each region in the neighborhood of analysis, an approach was constructed from the Cox method for estimating confidence intervals and the Z-score method for comparing the means of two independent lognormal distributions (Olsson 2005; Zhou et al. 1997).

2.2.2 Estimation of parameters

For approximately lognormal distributions, where $\ln X \sim N\left(\mu_n, \sigma_n^2\right)$, hypothesis testing developed by Zhou et al. (1997) can be applied for comparing samples with unequal variances as follows:

$$Z = \frac{\hat{\mu}_{n,2} - \hat{\mu}_{n,1} + (1/2)(S_{n,2}^2 - S_{n,1}^2)}{\sqrt{\frac{S_{n,1}^2}{n_1} + \frac{S_{n,2}^2}{n_2} + (1/2)\left(\frac{S_{n,1}^4}{n_1 - 1} + \frac{S_{n,2}^4}{n_2 - 1}\right)}} \qquad (1)$$

where $\hat{\mu}_n$ and S_n^2 are maximum likelihood estimators of the sample mean and unbiased estimators of the sample variance, respectively.



(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Fig. 4 Climate change (CC); kilogram of CO_2-eq per use: The scenario marked by a *circle* in (**a**) is one of a range of scenarios and corresponds to parameter uncertainty analysis in (**b**)

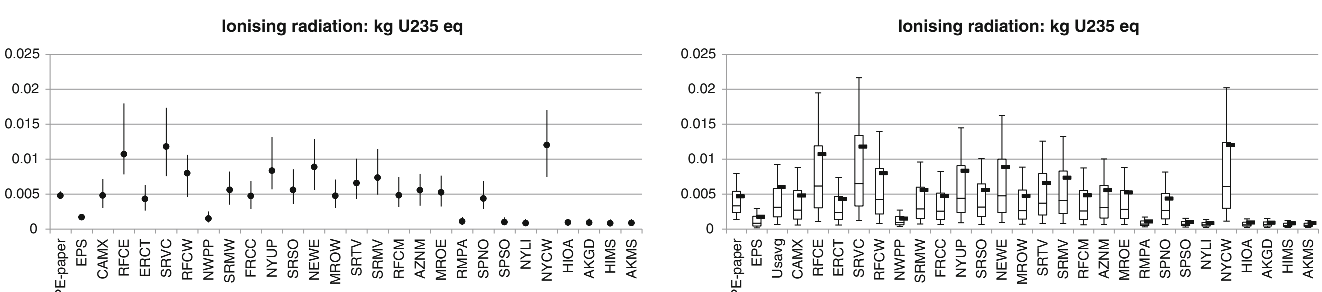
To perform the comparison, the Cox method for estimating confidence intervals is used to estimate S_n^2 and $\hat{\mu}_n$ with knowledge on the upper and lower bound of the intervals at 95 % confidence. The full equations are given in the Supporting Information.

3 Results and discussion

Following this approach, tables were constructed for comparing sample means, $\mu_{s,\mathrm{EPS}}$ and $\mu_{s,\mathrm{reuse}}$, for each region and scenario by the Z-score test. For example, inventory uncertainty for substances characterized for radiative forcing, or climate change, is relatively low. In this case, visual inspection of Fig. 6 would lead closely to the Z-score results, where a green circle indicates the reusable cup has a lower impact than the EPS cup for the relative US region and appliance efficiency. A red diamond indicates a lower impact for EPS, while a yellow triangle indicates no significant difference. One way to consider these results is to note that, of the top ten most populous US cities, only one city (Chicago, IL) is located in a subregion (RFCW) with higher climate change impact for the 2004 units. The other nine are in the regions CAMX, AZNM, SRMV, ERCT, RFCE, and the New York cluster. Climate change is influenced by utility mix and is correlated with cumulative energy demand only insofar as the utility is CO_2-intensive.

There is significant transmission across colocated subregions, so Fig. 6 is organized by subregional utility groups, shown as boxed groups in the icon chart in approximately decreasing order of regional population. Where the distribution of Z in Eq. 1 is approximately standard normal, significance was set as exceeding a score of ± 1.96 for 95 % confidence. Graphs and Z-score icon tables demonstrate model uncertainty in terms of region and energy efficiency of the appliance coupled with the parameter uncertainty communicated by the error bars. Figure 6 shows the nine subregions with the highest percentage of coal for electricity generation have the highest scores for climate change. This is according to the 2009 figures. After presenting the results, the discussion will address how the changing utility mix and other considerations would impact conclusions further.

Similar to ionizing radiation having higher variance, results for particulate matter (PM) formation, shown in Fig. 7, are skewed with greater spread making comparison of means less straightforward. For almost all regions, the best available technology has significantly lower impact for reusable cups. For units as efficient as the 2004 model average purchase, there is not a significant difference between



(a) Sensitivity analysis (scenario and model uncertainty) (b) Parameter uncertainty (Usavg = U.S. average)

Fig. 5 Ionizing radiation (IR); kilogram of U235-eq per use: The scenario marked by a *circle* in (**a**) is one of a range of scenarios and corresponds to parameter uncertainty analysis in (**b**)

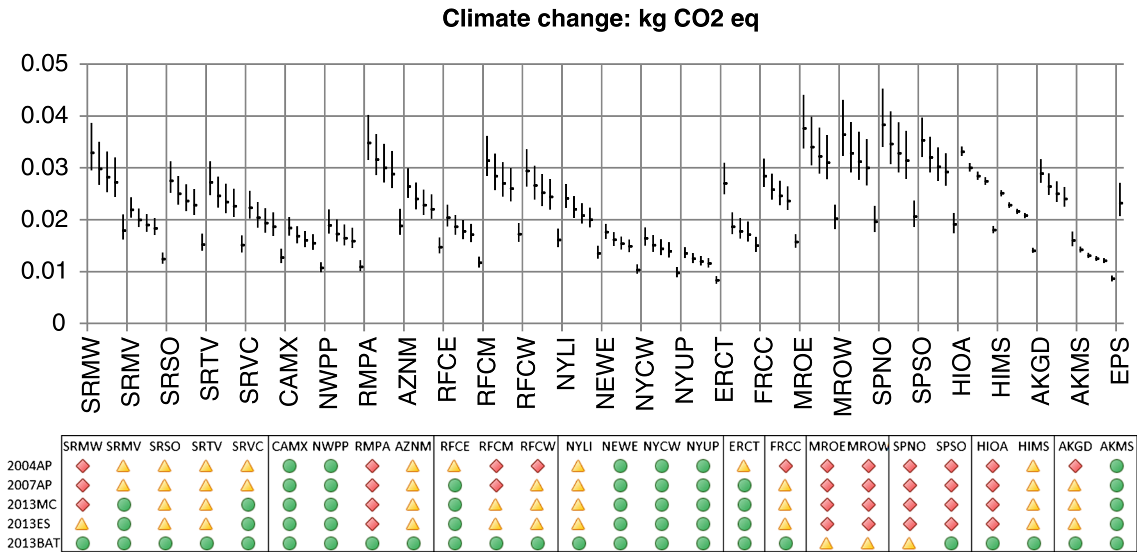


Fig. 6 Results across five models (described in Table 1) for climate change (kilogram of CO_2-eq per use): mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions

the two cup types, except in the subregion RFCM, which is roughly the Michigan lower peninsula.

Remaining ReCiPe midpoint results are available in the Supporting Information. All impacts except land use and water depletion categories were correlated entirely to energy use in the dishwasher. For all of these categories, except ozone depletion (OD) and climate change, results are either not significantly different or else favor reusable cups. For ozone depletion, impact is mostly correlated to nuclear power generation. Only SRVC and RFCE, which have the highest percentage of nuclear power, have higher impact for best available technology in this category. There are some CFC emissions associated with uranium enrichment in the inventory. In contrast, most regions with higher ozone depletion values score significantly lower for climate change.

Land use was considered outside of the scope of this comparison. Water depletion and metal depletion showed higher impact for reusable cups. While water depletion for EPS is embodied water, that for reusables is throughput, which is not consumed. The reason being that water depletion was calculated in the method almost entirely from the draw of tap water for washing. Only a small percentage of the results were due to evaporative losses or embodied

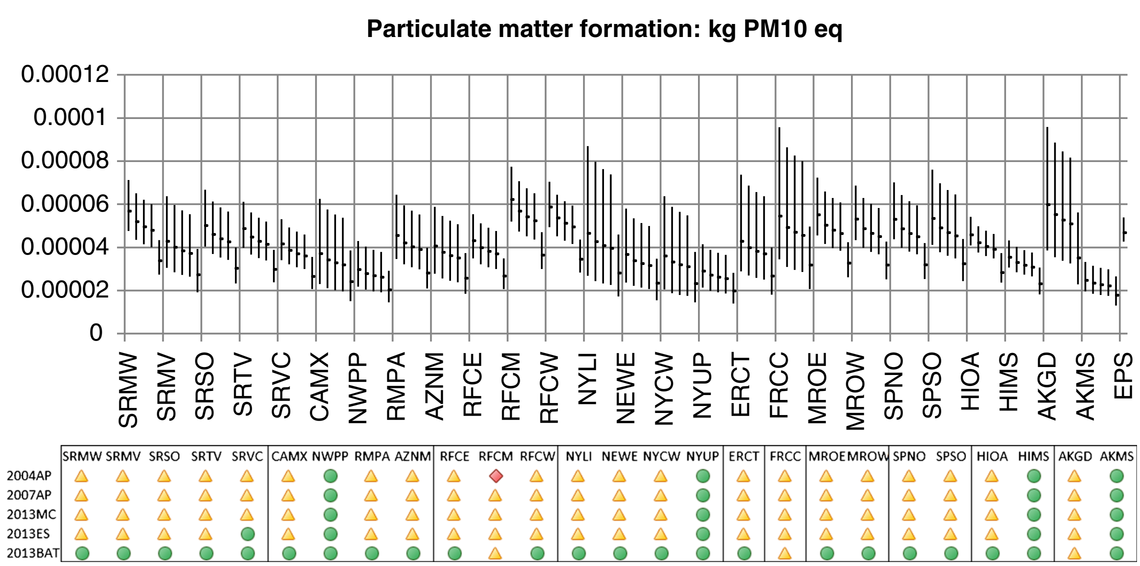


Fig. 7 Results across five models (described in Table 1) for climate change (kilogram of PM10-eq per use): mean of EPS (μ_{EPS}) is compared to each regional mean for ceramic mugs ($\mu_{reuse,region}$) by Z-score comparision of two independent lognormal distributions

water, leaving the results to be interpreted as throughput not depletion of water. It is debated how water may be incorporated into LCA studies by impact rather than throughput; Ecoinvent reports water use, not consumption (Berger and Finkbeiner 2012).

Similarly, metal depletion results are based on the amount of copper used in transmission and distribution. The copper is considered depleted by reference of having been extracted from the Earth, but forming into electrical cables is not a dissipative activity such as incorporation of copper to circuit boards or consumer electronics, leaving this category open to interpretation, since the method would consider copper for either aggregate or dissipative activities equivalently.

Reusable cups meet at least two of three strategies laid out for maintaining quality of life with lower rates of new product purchasing: life extension, shared ownership, and product repair (Allwood et al. 2011). Results presented show that, for many regions across the USA, reusable cups are a better choice than polystyrene cups for typical serving sizes when washed in a standard-sized dishwasher once for every use. It is reasonable to assume that an individual using a reusable cup is more likely to rinse and reuse a cup throughout the day if it is a personal item than if it is a single-use item. Performing the same procedure for the SRMW subregion assuming an average of two uses per wash resulted in improvements in all indicators. For the 2004 average purchased model in climate change and particulate matter formation, the impact is less than the single-use polystyrene disposable and is lower than one use per wash with the best available technology. Ozone depletion impact was lowered from worse to not significantly different. Details are in the Supporting Information.

According to the Energy Information Administration's Electric Power Annual for 2011, green pricing has been entirely driven by the residential sector, where 92.9 % of green pricing customers are residential, 7 % commercial, and 0.1 % industrial (U.S. Energy Information Administration (EIA) 2013). This implies that credit for cleaner portion of utility mixes goes to the residential consumer for electricity use in the home.

The impact of a changing utility mix with higher penetration of renewable technologies and the increased domestic availability of natural gas also leads to additional conclusions. Net capacity additions for natural gas-fired and renewable generators continue to increase with 56.8-GW net summer capacity additions in natural gas, wind, and solar predicted for 2012–2016 (U.S. Energy Information Administration (EIA) 2013). For the same period, net summer capacity for coal-fired generators is expected to decrease by 4.1 GW. The current condition for SRMW was investigated to compare the impact from the 2009 eGrid mix to 2012 figures reported by the US Energy Information Administration (U.S. Energy Information Administration (EIA) 2012). Applying the same analytical approach, improvements were seen in all impacts. Details are in the Supporting Information.

One final item of consideration in interpreting the results is interstate electricity imports. Electricity import and export of colocated regions is a function of the population and business distributions. Nonetheless, interstate transmission is assumed to impact comparative results minimally. According to analysis by Marriott and Matthews (Marriott and Matthews 2005), outside of California, most of interstate transmission occurs between states that are already assessed as regional groups. For example, WV exports to VA and MD, both of which partially belong to RFCE as does WV. Similarly, while CA imports a significant amount, it is generally coming from other WECC regional states, not including RMPA.

Finally, while a demonstrative study, it has been implied by Lave et al. that disposable cups may have higher indirect impacts through supply chain interactions than those directly captured in process LCA (Lave et al. 1995). To the contrary, where the supply chain for electricity production is less complex than for consumer goods, it is thought that process LCA for electricity production in this study effectively captures most impacts.

Using LCA methodology, the authors intend the framework of this study to be used as guidance for corrective measures in reporting results of life cycle impact assessments. Unlike the headline "Single-use cups win every time!" claimed by the Benelux Disposables Foundation after publication of the TNO report, this study makes no claim of the ultimate superiority of any cup system (Stichting Disposables Benelux 2013). It is considered the best available guidance for US consumer choice in single-use and reusable cups with respect to regional power mix and consumer behavior.

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